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Electronic Systems for the Protection of Superconducting Elements in the LHC

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Abstract

The Large Hadron Collider LHC, currently under construction at CERN, will incorporate an unprecedented number of superconducting magnets, busbars and current leads. As most of these elements depend on active protection in case of a transition from the superconducting to the resistive state, the so-called quench, a protection system based on modern, state of the art electronics has been developed.

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Electronic Systems for the Protection of Superconducting Elements in the LHC

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Index Terms—Control equipment, electronic equipment, protection, superconducting accelerator magnets

I. INTRODUCTION

THE Large Hadron Collider LHC [1], which is presently under construction at CERN, will incorporate a large amount of superconducting elements like magnets, current leads and busbars.

If a segment of such an element is undergoing a transition from the superconducting to the resistive state whilst powered, this may lead to a thermal runaway situation, the so-called quench. In most cases this will require a means of active protection in order to ensure the integrity of the element concerned. The protection systems have been developed over the last years at CERN and produced by European industry as well as within worldwide collaborations with other research institutes. A major part of these systems has been already delivered to CERN and is currently being tested, installed and commissioned.

II. PROTECTION OF THE LHC MAIN MAGNETS

The protection of the LHC main dipole and quadrupole magnets, which are powered in series of 154 and 47/51 magnets respectively, is ensured by cold by-pass diodes [2], individual quench detection systems, quench heaters with the corresponding power supplies [3] and energy extraction facilities [4]. The quench detection system, the associated data acquisition system and the quench heater supplies are integrated into protection racks, which are located inside the LHC tunnel underneath the main dipole magnets

A. Analog quench detection system

The quench detection system is based on an analog design

implementing a Wheatstone bridge configuration formed with the magnet coils and balancing resistors. The detector design is redundant and based on two identical detection boards in a hardwired logical OR configuration. In order to reduce the number of faulty triggers each board is equipped with a redundant input and detection stage using a two out of two evaluation scheme [5]. The board is completed with a small data acquisition system including an analog output channel for the generation of test signals for the detection system. Table I summarizes the basic parameters of the detection and data acquisition system.

TABLE I
MAIN MAGNET QUENCH DETECTION SYSTEM - BASIC DEVICE PARAMETERS

Device Parameter	Value
Units in LHC (two redundant circuit boards per unit)	2016
Detection threshold	± 100 mV
Discrimination time	10.5 ms
Differential input voltage range	± 200 V
Maximum differential input voltage	± 726 V
Isolation to common ground (detection board on magnet potential)	3.1 kV
Radiation tolerance: total integrated dose	200 Gy
Radiation tolerance: fast neutron fluence	10^{12} ncm ⁻²
Data acquisition system:	
Analog input channels	4
High resolution (0.21 mV) analog input range	± 0.25 V
Low resolution (172 mV) analog input range	± 206 V
Sampling frequency	193 Hz
Data buffer length	12.75 s
Analog output channels	1
Analog output channel range	± 0.25 V

B. Interlock system

Once a quench has been detected, the quench heater power supplies are triggered and the hardwired interlocks, which are based on current loops, are activated. These interlocks include as well the energy extraction facilities and the protection systems for the high- T_c superconducting current leads [6] and the superconducting busbars. The state of the current loops is monitored at both ends of an LHC sector and transmitted to the corresponding powering interlock controllers [7], which will take the necessary actions in order to stop the accelerator and dump its beams safely. At the same time the energy extraction facilities will be activated and the discharge of the superconducting circuit will start. Fig. 1 shows the layout of the interlock loops for the LHC main circuits and Fig. 2 explains the sequence of events in case of a main magnet quench. It is noteworthy that the complete

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interlock chain involving the powering and beam interlock controllers ensures that the beams are dumped before the current in the magnets starts decreasing.

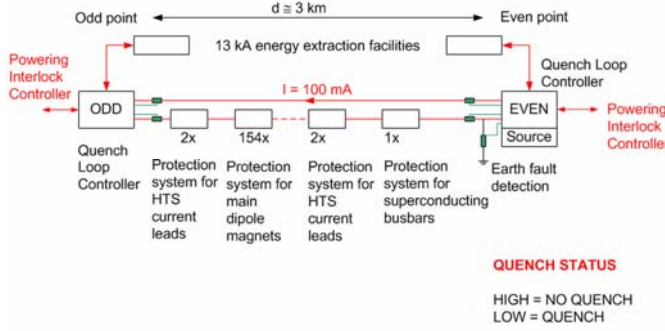


Fig. 1. Layout of the interlock current loop for the LHC main circuits.

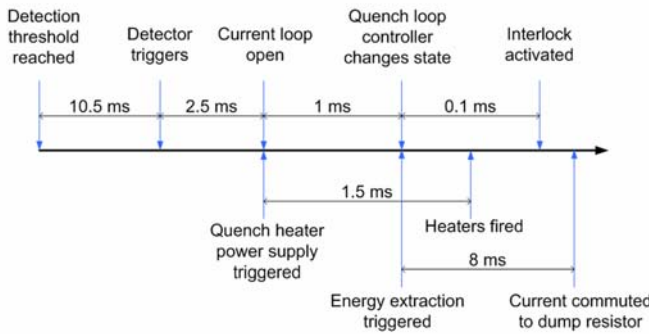


Fig. 2. Event sequence in case of a main magnet quench.

III. DIGITAL QUENCH DETECTION SYSTEMS

Digital quench detection systems [8] will be used for the protection of corrector magnets, insertion region magnets, superconducting bus-bars and high- T_c superconducting current leads. All these systems are placed in protected underground areas, where the radiation levels during LHC operation are expected to be significantly lower than inside the LHC tunnel and no specific radiation tolerance of electronic equipment is required.

All digital detection systems are redundant using a hardwired 1 out of 2 evaluation scheme.

A. Fast DSP based general purpose detection system

For the protection of LHC superconducting insertion region magnets, inner triplets as well as for those corrector magnets which have an ultimate current rating of 600 A, a general purpose two channel digital detection system has been developed. Hereby the protection covers the magnet and the respective superconducting busbar.

The core of the system is a digital signal processor DSP of the TMS320C6211TM type using two 14 bit analog-digital converters for the evaluation of the two analog input channels. In addition the system disposes of a two channel digital-analog converter, which is used for the generation of test signals as well as for the measurement of slowly varying input voltages.

Each of the 600 systems in the LHC is pre-configured with the circuit and quench protection parameters. Normally a common detection threshold of 100 mV and an evaluation time of 10.5 ms are used. It is foreseen to update specific circuit parameters, like the inductance, dynamically during powering of the corresponding superconducting circuits.

For the protection of corrector magnets the detection system is configured in differential mode using the second analog input channel for measuring the current in the superconducting circuit with the help of a dedicated current sensing device. In the case of the insertion region and inner triplet magnets the two input channels will be used to create a numerical bridge configuration.

These digital protection systems have the main advantage that they require less instrumentation wires and are adaptable to the actual circuit parameters in a more flexible way than an equivalent analog system. The quite sophisticated software and the additional time required for the final commissioning of the first systems during powering of the superconducting circuits are drawbacks.

B. High precision protection systems

The protection system of the about 1200 hybrid high- T_c superconducting current leads consists of two dedicated detection channels for the resistive and superconducting part of the lead. The latter requires a high precision detection system, which is able to handle the low detection threshold of 3 mV in an electromagnetically noisy industrial environment. The design is based on the ADuC834TM micro-controller, which is equipped with an integrated 24 bit analog-digital converter of the Sigma-Delta type. The analog input stage is built with INA141TM instrumentation amplifiers exhibiting a minimum common mode voltage rejection of 117 dB.

C. Integration of the digital protection systems

The fast and high precision systems are grouped together according to the circuits and integrated into so-called global protection units, which are capable to protect independently up to 4 superconducting circuits (see Fig. 3).



Fig. 3. Global protection unit protecting up to 4 corrector magnet circuits.

D. Protection of the LHC superconducting main busbars

In the special case of the superconducting busbars feeding the LHC main circuits a cluster of high precision detection boards similar to those described above is linked together with the help of a dedicated fieldbus network. This forms a distributed detection system managed by a master computer. The design takes advantage of the fact that the selected fieldbus of the WorldFip™ type is deterministic in time, thus allowing the implementation of a real time software application. Fig. 4 shows the layout of the system, which is distributed over a complete LHC sector.

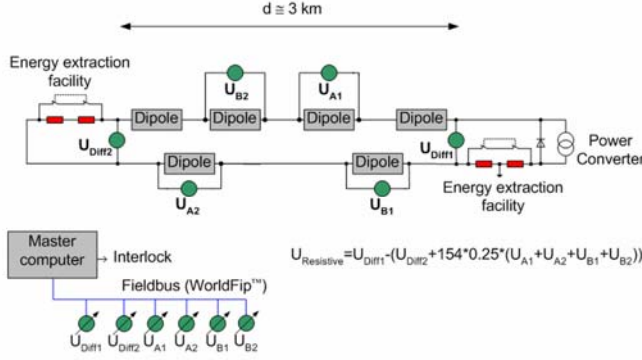


Fig. 4. Distributed quench detection system for the protection of LHC main busbars. The presented layout refers to the main dipole circuit.

IV. DATA ACQUISITION SYSTEMS

The supervision of all the quench protection electronics and the energy extraction facilities is based on fieldbus controlled data acquisition systems, called acquisition and monitoring controllers. These controllers are part of the electronic protection assemblies and communicate with the supervised equipment via galvanically isolated local serial busses either of the I2C™ or SPI™ standard. The design incorporates various building blocks and can be easily adapted to different supervision requirements. All systems are individually programmed according to their functional position in LHC. The basic technical parameters are shown in Table II.

TABLE II
FIELDBUS CONTROLLED DATA ACQUISITION SYSTEMS

Parameter	Value
Units in LHC (4 variants)	2100
Analog input channels	Up to 8
Digital I/O channels	Up to 80
Fieldbus protocol	WorldFip™, 1 Mbit/s
Systems per fieldbus segment / gateway computer	Up to 60 / 120
Local serial bus interfaces	SPI™, I2C™
Sampling frequency	193 Hz
Data exchange rate with gateway computer	480 byte/s upstream, 80 byte/s downstream
Radiation tolerance (only valid for the variant to be installed inside the LHC tunnel)	Total integrated dose: 200 Gy Fast neutron fluence: 10^{12} ncm ⁻²

A. Interface with the accelerator control system

All information, which is exchanged between the accelerator control systems and the acquisition and monitoring controllers passes through gateway computers [9]. The communication between the acquisition and monitoring controllers and the gateway computers, which are located in surface buildings, happens by means of a fieldbus network of the WorldFip™ standard. Hereby a cyclic communication protocol has been implemented, which is fully deterministic in time. Each of the so-called WorldFip™ macro-cycles lasts 200 ms and consists of only three different steps, namely the emission of the variables time and command by the gateway computer and the reception of the variable data.

B. Post mortem data

All data collected by the detection electronics and the acquisition and monitoring controllers are stored temporarily in local time-stamped circular buffers. The size of these buffers is adapted to the specific task of the respective device and reaches from 12.5 seconds for most of the quench detection systems up to several minutes for the energy extraction facilities. After a post mortem event (e.g. a magnet quench) the buffering process is stopped and the content of the buffer is sent to the corresponding gateway computer. This task can be completed in less than 10 minutes, the hold-up time of the uninterruptible power supplies.

C. Timing and synchronization

In order to be able to analyze post mortem data generated in case of a post mortem event properly and to correlate it with data from other accelerator systems, e.g. the powering interlock controllers, that all acquisition and monitoring controllers must be synchronized with a precision of one millisecond with respect to the accelerator time.

Within one fieldbus system synchronization is ensured by the emission of a global variable, which contains the accelerator time and creates a hardware interrupt read out by the controller firmware. A similar mechanism links also the associated detection systems with the controllers and synchronizes the various fieldbus segments.

It has to be emphasized that a timing failure or a lack of synchronization will not affect the proper function of the quench detection systems.

V. QUALITY ASSURANCE AND TEST

Very thorough quality assurances and test procedures are being applied to meet the very high demands on the availability and reliability of all quench protection electronics.

A. Tests during manufacturing

All manufacturers are contractually obliged to follow test and quality assurance procedures according to respective production standards. In addition a series of dedicated automated functional test systems has been developed and constructed at CERN and installed at the respective manufacturer's premises. In both cases 100% of all produced

units have to pass successfully the test procedures.

B. Surface tests

The final assembly, programming and test of all protection systems takes place at CERN. Each completed assembly first has to pass an isolation test, which is followed by the download of the final firmware versions to the quench detection systems and the acquisition and monitoring controllers. After that the system is submitted to an exhaustive functional test, which covers all aspects of protection and supervision. The tests comprise among other things the verification of quench detection thresholds and evaluation times, the discharge of quench heater power supplies into dummy loads, the measurement of the DC transfer functions of all analog input stages and a check of the test mode functionality. All these tests are fully automated including the evaluation of the test using specially developed test software [10]. Fig. 5 shows the test facility for main magnet protection racks, capable of testing up to 4 systems in parallel. Due to its complexity a typical test lasts about 3 hours yielding to a daily maximum test rate of 12 racks per day. In case that non-conformities are revealed during the test, the failing device will be replaced and the complete assembly re-tested.



Fig. 5. Test facility for main magnet protection systems. The systems are already conditioned with respect to the later transport and installation in the LHC.

C. Individual system tests after equipment installation

After installation in the LHC all quench detection electronics has to be carefully tested prior to the first powering of the superconducting circuits. After visual inspection of all cable connections and a cross check of the equipment's name and functional position, the device is powered up and the communication with the appropriate gateway computer is verified. Having passed this first step successfully, all further tests are conducted remotely via the corresponding gateway computers. Hereby the built-in test mode functionality is used to trigger interlocks and verify the proper functioning of the detection electronics.

Once the protection system has been fully commissioned a

subset of these tests has to be repeated on a monthly basis in order to guarantee its reliability and availability [5].

VI. CONCLUSION

Over the last years electronic systems for the protection of superconducting elements in the LHC have been developed at CERN. With the end of the production phase approaching final testing and preparation for installation in the LHC has started. After installation all these systems will undergo another functional test phase prior to the first powering of the LHC superconducting circuits, when these systems have to be fully operational.

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